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**Citation for published version:**

Wu, M & Flynn, D 2018, An Advanced Gas Metal Arc Welding Machine Design for Low Spatter Welding. in *2018 IEEE 27th International Symposium on Industrial Electronics (ISIE)*. International Symposium on Industrial Electronics (ISIE), IEEE, pp. 335-340, 2018 IEEE 27th International Symposium on Industrial Electronics, Cairns, Australia, 12/06/18. <https://doi.org/10.1109/ISIE.2018.8433865>

**Digital Object Identifier (DOI):**

[10.1109/ISIE.2018.8433865](https://doi.org/10.1109/ISIE.2018.8433865)

**Link:**

[Link to publication record in Heriot-Watt Research Portal](#)

**Document Version:**

Peer reviewed version

**Published In:**

2018 IEEE 27th International Symposium on Industrial Electronics (ISIE)

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# An Advanced Gas Metal Arc Welding Machine Design for Low Spatter Welding

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**Abstract**—In the short-circuiting metal transfer in gas metal arc welding (GMAW), melted metal explosions occur when the arc is re-ignited after the short circuiting. This can result in spatter on and around the welding beam especially when the shielding gas is the carbon dioxide. The spatter requires extra cleaning work after welding. Many investigations and patents have been made to reduce the spatter in GMAW by fast regulation of the output current. This fast output regulation can reduce 50% to 80% amount of spatter, which highly increases the productivity and reduces the cleaning work. The main objective of this paper is to experimentally demonstrate the effectiveness of the fast regulation of the output voltage and output current with the proposed hybrid control method in the GMAW application. Both bandwidth of the voltage and current control loop are about 4 kHz.

## I. INTRODUCTION

Gas metal arc welding (GMAW) is a very popular arc welding method for joining of metal due to its advantage of high speed and almost all kinds of metal welding [1]–[3]. GMAW is also named as metal inert gas (MIG) welding or metal active gas (MAG) welding, depending on the types of shielding gas used in the GMAW. Short-circuiting metal transfer is one of the common metal transfer approaches in GMAW. The circuit diagram of a conventional GMAW machine is shown in Fig. 1 [4]. An isolated DC/DC converter is used to supply a desirable power for welding. The output voltage of the machine is regulated because in GMAW a constant voltage source is required [5], [6]. Different from the operation of a conventional DC/DC converter, short circuiting repetitively occurs in GMAW. Therefore extra control circuit is required to implement inductance function which determines the increasing rate of the output current after the occurrence of the short circuit, and also to implement slope function which determines the maximum output current during the short circuit phase of the GMAW. In addition, large output capacitor is not used in GMAW machine due to short circuit operation. The output current and output voltage waveforms and the short-circuiting metal transfer in a conventional GMAW are illustrated in Fig. 2 [7].

As shown in Fig. 2, the arc is diminishing around  $t_1$ . Then, at  $t_2$ , when the melted metal at the end of the wire touches the welding pool, short circuiting will occur. Since the welding machine provides constant voltage for welding,

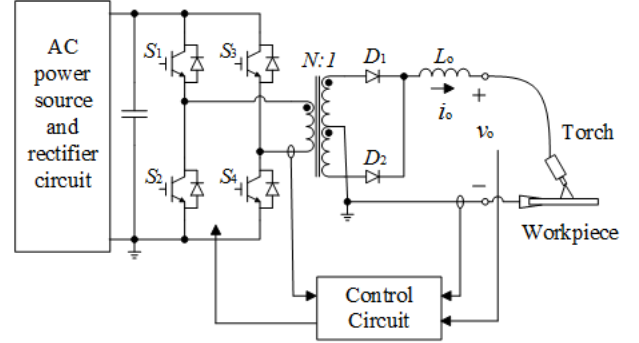


Fig. 1. Circuit diagram of a conventional GMAW machine.

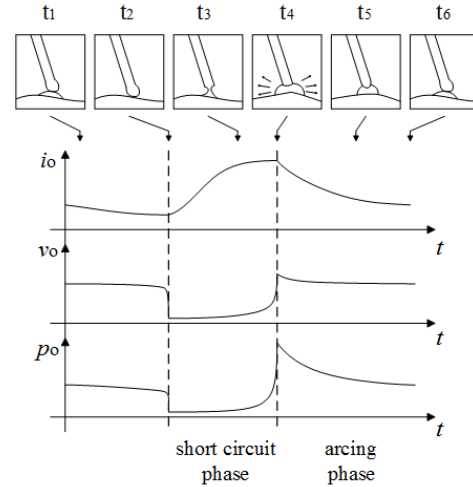


Fig. 2. Waveforms of the output voltage and output current and illustration of short-circuiting metal transfer in a conventional GMAW.

from the point of short circuiting, the voltage drops and the current starts to increase, and the melted metal starts to transfer from the wire to the welding pool. Due to the inductance function of the control system, the current will not increase rapidly but with a slow slope. The current increases to a high level at  $t_3$ , which can generate magnetic force to pitch the connection between the wire and welding pool. When the wire is disconnected from the welding pool at  $t_4$ , the arc will

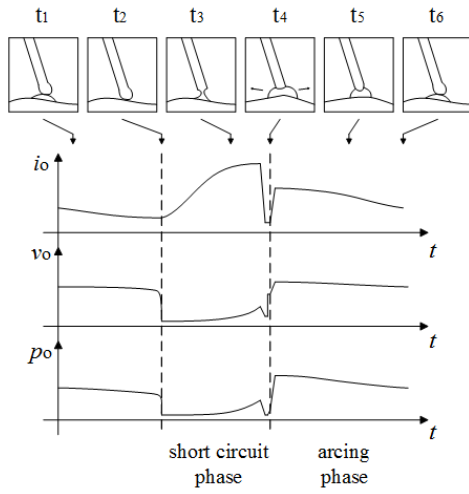


Fig. 3. Waveforms of the output voltage and output current and illustration of short-circuiting metal transfer in the low-spatter GMAW.

be re-ignited, and the voltage will suddenly increase and the current will start to drop. It can be noticed that at  $t_4$ , the time of the arc re-ignition, the output power is the maximum, which can cause explosion of some melted metal and spray it around the workpiece, causing spatters. After that, at  $t_5$ , the arc continuously generates heat to melt the end of the wire to form a melting ball for next short circuiting metal transfer. Then, at  $t_6$ , when the wire approaching the welding pool, the arc starts to diminish, and the above procedure will repeat.

In order to reduce the spatter generated at  $t_4$ , the power generated at that point needs to be reduced. An effective way of doing this is to reduce the current rapidly to a minimum level just before the arc re-ignition [8]. The waveforms of the output current, voltage and power in this method are illustrated in Fig. 3.

In Fig. 3, before arc re-ignition, the current is rapidly reduced to the minimum level to wait for re-ignition. When the arc is reignited at  $t_4$ , since the current is in the minimum level, the power is in the minimum level as well. As a result, the minimum level of spatter will be generated. After the arc re-ignition at  $t_4$ , current starts to increase to melt the end of the wire for the next cycle.

In addition to the reduction of the spatter, more accurate and fast output current or output voltage regulation can also implement different functions in different welding applications, for example, cold arc welding for thin material, deep penetration for thick material, fast speed welding for high production and etc. Several welding machines manufacturers, such as Lincoln, Miller, Fronius, EWM, and etc., have investigated current regulation for low-spatter GMAW [9]. A set of desired current and voltage waveforms in Surface Tension Transfer (STT) proposed by Lincoln are illustrated in Fig. 4 and can be explained as follows [10]. There are two control modes in the advanced GMAW machine, i.e., current control and voltage control. During short circuit phase, the machine operates under current control and the output current is regulated

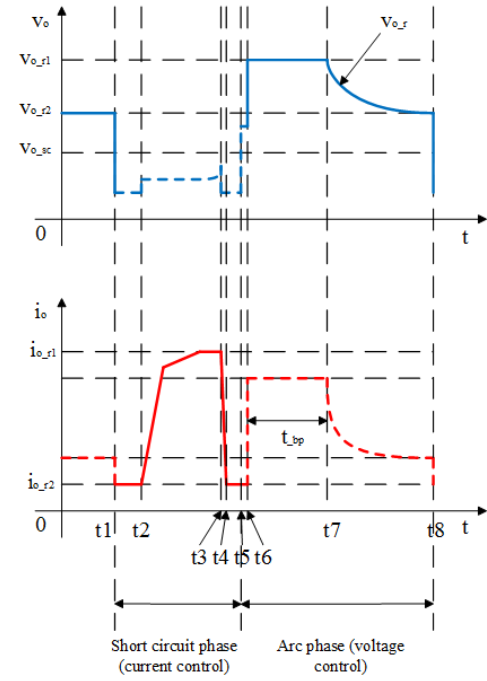


Fig. 4. Details of the voltage and current waveforms in the new control strategy.

to track the reference current signal as shown in red solid line, while during arcing phase, the machine operates under voltage control and the output voltage is regulated to track the reference voltage signal as shown in blue solid line. When short circuit occurs at  $t_1$ ,  $v_o$  drops below a threshold value,  $v_{o\_sc}$ , to indicate the occurrence of the short circuit. Then, the machine is switched to current control. From  $t_1$  to  $t_2$ , the output current will be regulated to be in the minimum level,  $i_{o\_r2}$ , to allow the occurrence of a firm short circuit. After  $t_2$ , the current starts to increase to generate magnetic force to pitch the connection between the wire and the welding pool. When  $i_o$  reaches to the maximum level,  $i_{o\_r1}$ , it will keep constant afterward. Since the cross-sectional area of the connection becomes smaller, the resistance of the connection becomes larger. Due to the constant current, the voltage becomes larger accordingly. When  $dv_o/dt$  reaches a certain value at  $t_3$ , which indicates that the connection is about to break, the output current is forced to reduce rapidly. When the output current reaches to  $i_{o\_r2}$ , the output current will be regulated to keep in the minimum current level to wait for the arc re-ignition. At  $t_5$ , the arc is re-ignited and the output voltage  $v_o$  increases over  $v_{o\_sc}$ , indicating that it is in arcing phase. Then the machine is switched to voltage control. From  $t_6$ , the output voltage is regulated to track  $v_{o\_r1}$  to allow high current to melt the end of the wire. After  $t_7$ , when a melted ball is formed at the end of the wire, the output voltage reduces to reduce the heat generated in the arc and wait for the next occurrence of the short circuit. At  $t_8$ , short circuit occurs and above procedure repeats.

This concept has been proposed and investigated by several

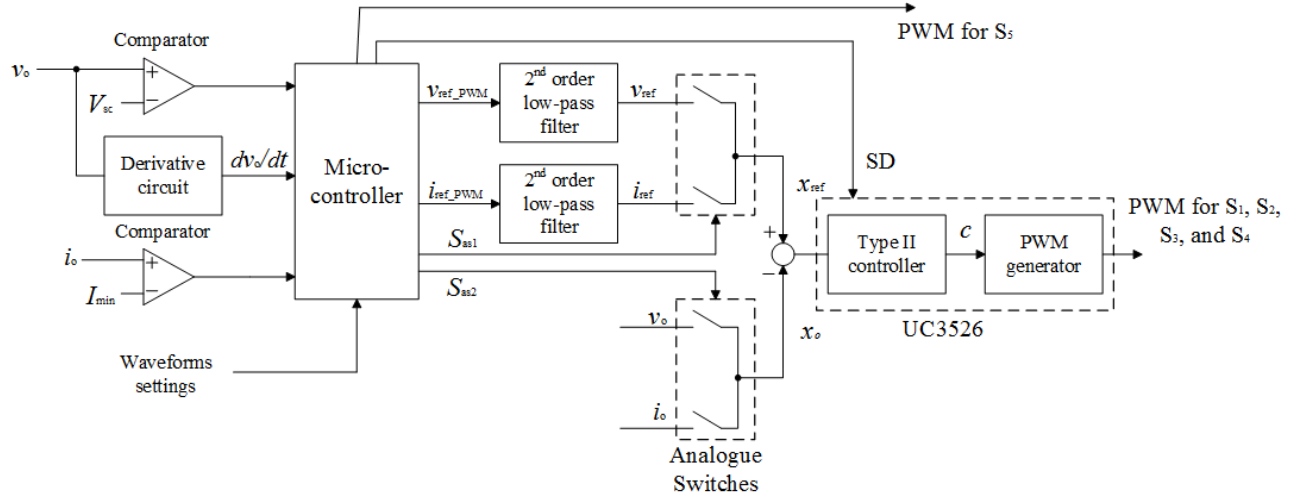


Fig. 5. Circuit diagram of the control system.

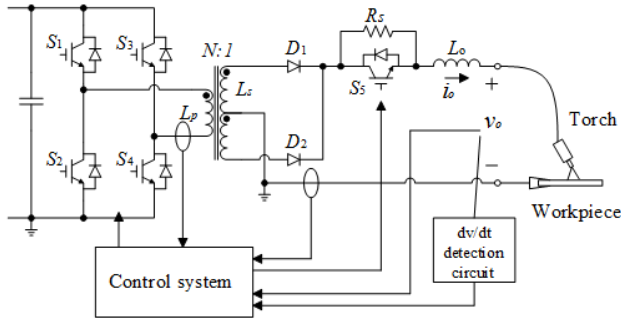


Fig. 6. Circuit diagram of the advanced GMAW machine.

patents, but implementation of this concept in the design of welding machine is not discussed in these researches. This paper proposes a hybrid control method for fast regulation of the output voltage and output current according to the desired waveforms. Both simulation and experimental results verify the effectiveness of the method.

This paper is organised as follows. The control system design is presented in section II. Simulation and experimental results are shown in section III. And finally, conclusions are given in section IV.

## II. CONTROL SYSTEM DESIGN

In order to implement the desired waveforms as shown in Fig. 4, both power stage circuit and control system need to be modified. In the power stage circuit, a semiconductor switch is added between the rectification diode and the output inductor as shown in Fig. 6. The function of this switch,  $S_5$ , is to achieve the fast speed reduction of the output current just before the arc re-ignition [11]. In the control system, a hybrid control circuit is proposed and designed as shown in Fig. 5.

The operation of the control system can be explained as follows. In general, a microcontroller is used to handle the information received from the user, for example, demand

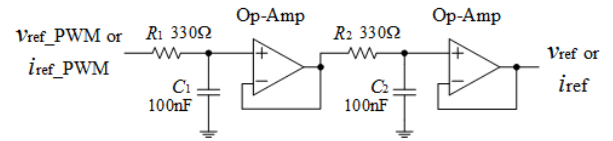


Fig. 7. Circuit diagram of the second order low pass filter.

voltage or demand current, and the welding process, for example, arcing phase, short circuit phase, or necking signal, and then to send demand signal to an analogue feedback controller accordingly. A high frequency PWM signals will be sent from the microcontroller to 2nd order low-pass filters to obtain analogue demand signals as shown in Fig. 5.

In order to obtain a fast speed response of the 2nd order low-pass filter. The cut-off frequency of the low-pass filter is high and as well as the PWM signals. In this control circuit, the cut-off frequency is 4.8 kHz, and the switching frequency of the PWM signal is 500 kHz. The circuit diagram of the 2nd order low-pass filter is shown in Fig. 7.

As explained in the above section and in Fig. 4, the GMAW machine is under voltage control in arcing phase and is under current control in short circuit phase. In order to design the feedback controller, small signal models of the full bridge DC/DC converter in arcing phase and short circuit phase need to be derived. The power stage circuit is a full bridge DC/DC converter as shown in Fig. 6. The small signal models of the full bridge DC/DC converter in arcing phase and short circuit phase are shown in Fig. 8(a) and Fig. 8(b), respectively.

In Fig. 8,  $V_{in}$  is the steady state value of the input voltage of the DC/DC full bridge converter,  $L$  is the combination of the inductance of the output inductor and the parasitic inductance of the welding cable,  $N$  is the turns ratio of the transformer,  $R_a$  is the small signal equivalent resistance of the load in the arcing phase, and  $R_{sc}$  is the small signal equivalent resistance of the load in the short circuit phase. From Fig. 8(a), the open

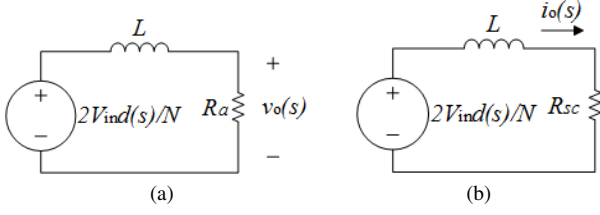


Fig. 8. Small signal model of the full bridge DC/DC converter in (a) arcing phase; (b) short circuit phase.

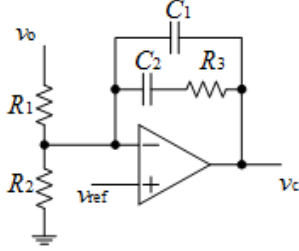


Fig. 9. Circuit diagram of the Type II controller.

loop transfer function from the duty cycle to the output voltage in arcing phase can be derived in (1).

$$G_{vd}(s) = \frac{v_o(s)}{d(s)} = \frac{2V_{in}R_a}{N(Ls + R_a)} \quad (1)$$

From Fig. 8(b), the open loop transfer function from the duty cycle to the output current in short circuit phase can be derived in (2).

$$G_{vd}(s) = \frac{v_o(s)}{d(s)} = \frac{2V_{in}}{N(Ls + R_{sc})} \quad (2)$$

Due to the similarity of (1) and (2), in the feedback controller design, a single Type II feedback control circuit as shown in Fig. 9 can be used for both current and voltage regulation.

The transfer function of the Type II controller is recalled in (3).

$$C_v(s) = \frac{v_c(s)}{v_o(s)} = \frac{1 + sC_2R_3}{sR_1C_2(1 + sC_1R_3)} \quad (3)$$

where,  $R_1$ ,  $R_2$ ,  $C_1$ , and  $C_2$  are the resistors and capacitors in the Type II controller as shown in Fig 9. In the calculation of the open loop transfer function of the closed loop system, transfer functions of the voltage and current sensing circuits are also need to be considered which are the gains,  $K_v$  and  $K_i$ , respectively. In addition, the transfer function from  $v_c(s)$  to  $d(s)$  is  $K_{PWM}$ .

Therefore, the open loop transfer functions of the closed loop system for the voltage control and the current control are  $K_{PWM}K_vG_{vd}(s)C_v(s)$  and  $K_{PWM}K_iG_{id}(s)C_v(s)$ , respectively.

The parameters of the full bridge DC/DC converter and the parameters of the Type II controller are listed in Table I and Table II, respectively.

TABLE I  
PARAMETERS OF THE FULL BRIDGE DC/DC CONVERTER

Name of the parameter	Notation	Value
Input voltage	$v_{in}$	560 V
Turns ratio of the transformer	$N : 1$	6.7 : 1
Output Inductor	$L$	20 $\mu$ H
Load resistance in arcing phase	$R_a$	0.1 $\Omega$
Load resistance in short circuit phase	$R_{sc}$	0.01 $\Omega$
Switching frequency	$f_s$	20 kHz

TABLE II  
PARAMETERS OF THE TYPE II CONTROLLER

Notation	$R_1$	$R_2$	$R_3$	$C_1$	$C_2$
Value	1 k $\Omega$	1 k $\Omega$	1 k $\Omega$	4.7 nF	100 nF

Given that  $K_v = 0.1$ ,  $K_i = 0.01$ , and  $K_{PWM} = 0.2$ . The Bode diagrams of the transfer functions  $G_{vd}(s)$ ,  $C_v(s)$ , and  $K_{PWM}K_vG_{vd}(s)C_v(s)$  in voltage control in arcing phase are shown in Fig. 10, and the Bode diagrams of the transfer functions  $G_{id}(s)$ ,  $C_v(s)$ , and  $K_{PWM}K_iG_{id}(s)C_v(s)$  are shown in Fig. 11.

From Figs. 10 and 11, it can be found that the voltage control bandwidth is 3.99 kHz and the phase margin is 76.4 degree, and the control bandwidth of the current control is 4.06 kHz and the phase margin is 66.3 degree.

### III. SIMULATION AND EXPERIMENTAL RESULTS

A simulation circuit is built in LTspice with the above parameters. The simulation results are exported from the LTspice and plotted in Matlab as shown in Fig. 12. From the simulation results, it can be found that the output voltage,  $v_o$ , as shown in Fig. 12(a), and the output current,  $i_o$ , as shown in Fig. 12(b), are regulated according to the reference voltage as shown in Fig. 12(c). Both the output voltage and the output current are stable.

A 200W power electronic converter circuit prototype has been built to verify the effectiveness of the control method. The experiment setup is shown in Fig. 13. The circuit of the

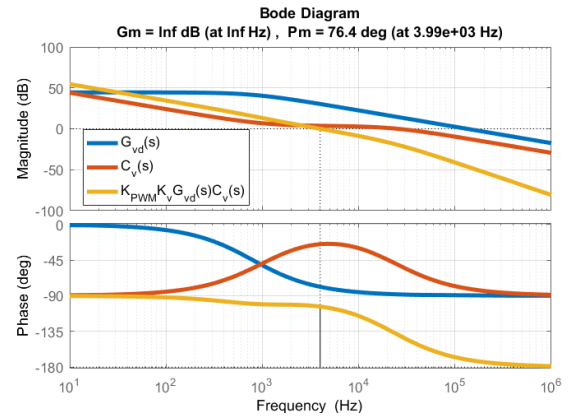


Fig. 10. Bode diagrams of the transfer functions  $G_{vd}(s)$ ,  $C_v(s)$ , and  $K_{PWM}K_vG_{vd}(s)C_v(s)$ .



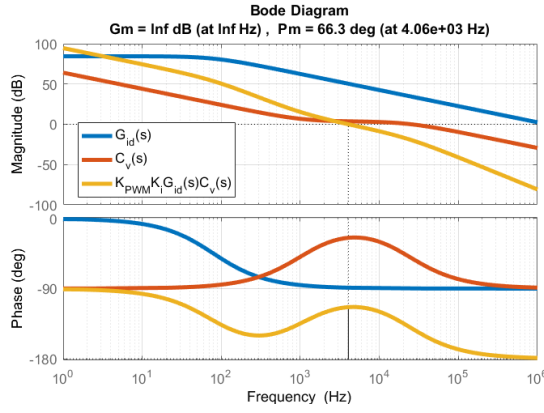


Fig. 11. Bode diagrams of the transfer functions  $G_{id}(s)$ ,  $C_v(s)$ , and  $K_{PWM}K_iG_{id}(s)C_v(s)$ .

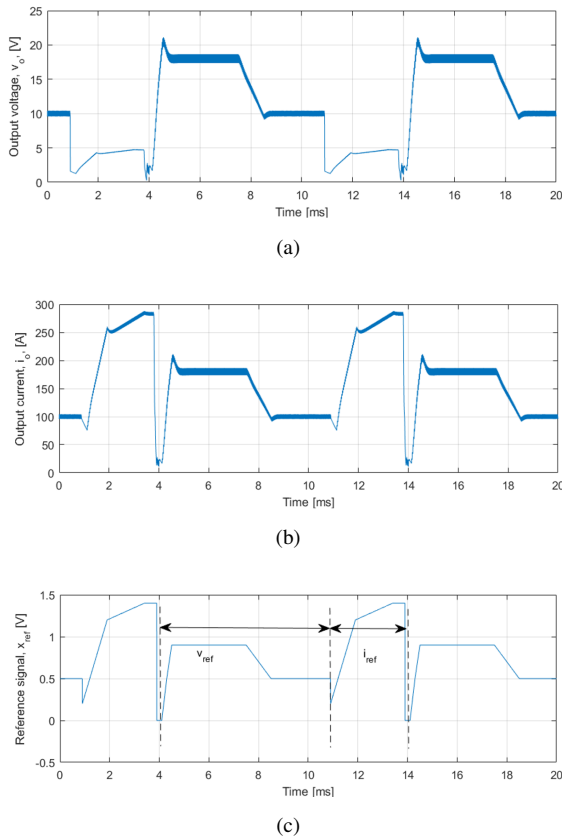


Fig. 12. Simulation results of (a) output voltage,  $v_o$ ; (b) output current,  $i_o$ ; (c) reference signal,  $x_{ref}$ .

power electronic converter prototype is the same as the circuit shown in Fig. 6, and the control circuit is the same as the circuit shown in Fig. 5. In order to simply simulate the load in the GMAW with short circuit transfer mode, a load circuit is designed and built as shown in Fig. 14. As shown in Fig. 14, a  $2\ \Omega$  load is used to simulate the load of the welding machine in the arcing phase, and this load is consisted by eight  $1\ \Omega$  resistors. A  $0.1\ \Omega$  load is used to simulate the load of the welding machine in the short circuit phase, and this

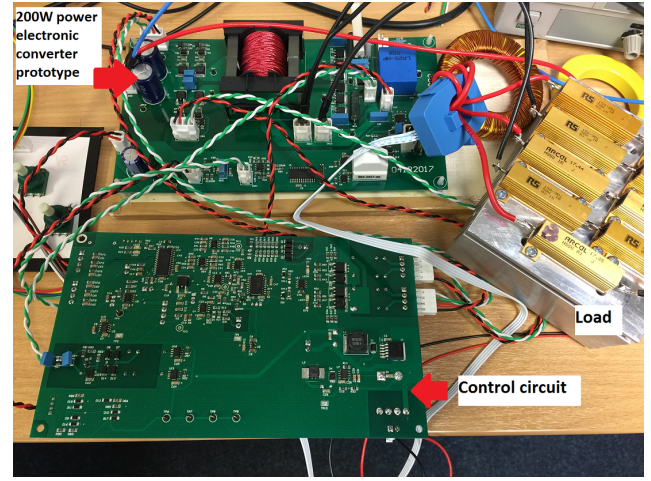


Fig. 13. Experiment setup of the 200 W power electronic converter prototype and the control circuit.

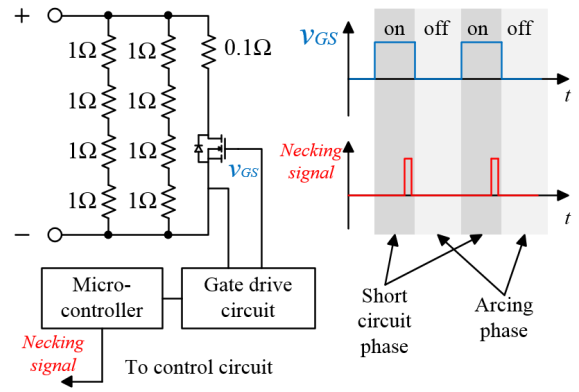


Fig. 14. Load circuit for imitating the short circuiting GMAW.

load is connected to the output of the power electronic circuit through a power MOSFET. This power MOSFET is controlled by a microcontroller to generate a repetitive arc phase and short-circuit phase operating conditions. The microcontroller also generates a necking signal which indicates that the short circuit phase is about to finish. In the GMAW machine design,  $dv_o/dt$  is normally sensed to detect the moment when the arc is about to reignite. In this experiment setup, the necking signal is used to simulate the detection of the moment just before the arc re-ignition. This signal is fed to the control circuit.

The experimental results are shown in Figs. 15-17. Fig. 15 shows the waveforms of the output voltage,  $v_o$ , and the output current,  $i_o$ , of the power electronic converter in arcing phase and short circuit phase operating conditions. It can be found that, under the advanced control method, the output voltage is regulated in arcing phase while the output current is regulated in short circuit phase. The details on the transition from arcing phase to the short circuit phase is shown in Fig. 16 from which it can be seen that after the occurrence of the short circuit the output current is under control and is maintained to be in a minimum level for a short period for time. As explained in

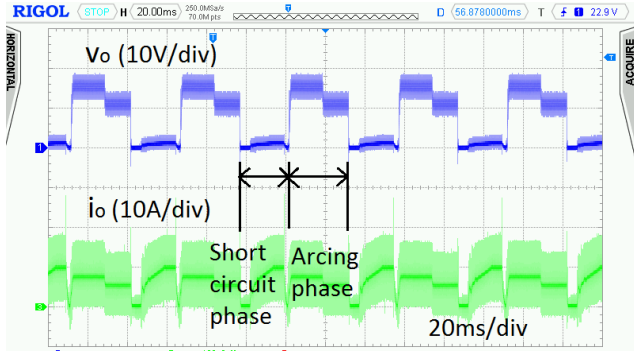


Fig. 15. Waveforms of the output voltage,  $v_o$ , and the output current,  $i_o$ , in the prototype circuit with the advanced control method.

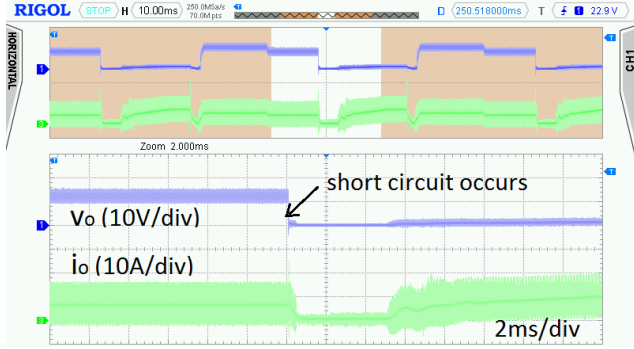


Fig. 16. Details of the waveforms in the transition from the arcing phase to the short circuit phase.

section II, keeping current to minimum level is to secure a firm short circuit and prevent incipient short circuit. After that, the output current is regulated to increase to pitch the connection for metal transfer. The details on the transition from short circuit phase to the arcing phase is shown in Fig. 17. As shown in Fig. 17, when the control circuit receives the necking signal from the load at point A, PWM generator in the control circuit will be turned off and  $S_5$  will be turned off to make a fast output current decrement. When the output current is reduced to a low level at point B, PWM generator and  $S_5$  will be turned on and the output current will be regulated to be a lower level before arc re-ignition. When arc is re-ignited at point C. The output voltage increases and the circuit works under voltage control. It can be found that at the point of arc re-ignition, the current level is regulated to be low, which can reduce the explosion power in the arc re-ignition and spatter.

#### IV. CONCLUSION

This paper demonstrated a hybrid control method to implement an advanced GMAW. The main advantage of this control is that it can reduce the amount of spatter during short circuit GMAW. In this method, the power supply for welding is under voltage control in arcing phase and under current control in short circuit phase. A digital controller is implemented to provide an agile solution to different requirements, for example, the occurrence of short circuits, necking signals, and



Fig. 17. Details of the waveforms in the transition from the short circuit phase to the arcing phase.

etc. The benefits of this hybrid solution with integrated digital control is in its ability to determine the optimal control mode and generation of the according demand signal, dependent on the specifics of the welding requirement. Utilising traditional components within an optimal circuit topology (hybrid) with digital control clearly provides advantageous performance and flexibility over traditional systems. A 200W power electronic converter prototype, load circuit for simulation short circuit GMAW process, and control circuit are designed and built to verify the effectiveness of this method and implementation. In the future work, a welding machine prototype with the proposed control method will be built to verify the spatter reduction in the welding process.

#### ACKNOWLEDGEMENT

The authors would like to thank Newarc Ltd. and Innovate UK for their funding support.

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